THE PROBLEMS OF MAN'S ADAPTATION TO THE LUNAR ENVIRONMENT

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INTRODUCTION

Man is provided with a number of sensory organs, namely, the eyes, the vestibular labyrinth, and the proprioceptive sensors which are interdependent in establishing man's equilibrium and orientation in the normal 1 g environment. These organs establish the postural vertical and control and coordinate the position and motion of the various parts of the body. Ordinarily little attention is paid to this innate capability and it is only when the cues from one or more of these organs are lost because of disease or as a result of a changed environment, that man is caused to consider the mechanisms of equilibrium.

The lunar environment provides only one-sixth of the gravity that man is normally subjected to and as a result there will be a direct reduction in the stimulation to some of the organs of equilibrium. This paper will concern itself with the effects of this reduced stimulus on the general senses of equilibrium and therefore on man's ability to orient and move about the lunar surface.

GENERAL CONSIDERATIONS

It is first necessary to identify those organs whose function is subject to changes in gravity and to determine the degree to which the organ will be affected. In 1952 it was postulated in reference 1 that zero gravity would have little effect on visual perception, this hypothesis apparently has been

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borne out by the recent orbital flights. Also, orbital flights have provided little indication that reduced gravity adversely affects the control of eye movements. However, the apparent increase in acuity in orbital flights is considered, as pointed out in reference 2, to be caused by an increase in physiological nystagmus due to a reduction of frictional and damping forces of the eye in zero g.

Because of the lack of atmosphere it is expected that there will be an increase in contrast on the moon which should affect depth perception. This, however, would not very likely have any effect on the visual contribution to orientation. Vision is, of course, susceptible to contradictory cues from the other sense organs (refs. 3 and 4); however, for a person using self-locomotion on the moon contradictory cues are not expected to be present. Therefore, it can be concluded that the eyes will be of primary importance for orientation in lunar operations. Eventually, manned lunar-surface vehicles will be employed and the possibility of vehicle-induced visual illusions will have to be considered.

As far as the vestibular system is concerned, it is anticipated that the semicircular canal function will not be affected by reduction in gravity since the canals are considered to be essentially angular acceleration sensors. The canals can only be affected by linear acceleration if differences exist in the specific gravity of the cupula and the endolymph fluid.

The otolith organ which is the linear acceleration or gravity sensor and the proprioceptive mechanisms will, of course, be directly affected by reduced gravity. It can be expected that with reduced stimulation of these organs and in the absence of vision man may have difficulty in judging the vertical. As reported in references 5, 6, and 7, this has been demonstrated, for the

situation of reduced proprioceptive cues, in tilt tests which showed that padding of the tilt chair or tilting the subjects in water decreased their accuracy in indicating the vertical. In these situations the stimulus to the otolith was normal.

Very little data exist on the effects of reduced otolith stimulation on equilibrium although many experiments to determine otolith threshold have been made. These threshold values are reported to be in a range from about 0.00034g to 0.010g which is much less than the 1/6 lunar gravity. However, these threshold values must be maintained for a certain length of time before being perceived and the minimum values of acceleration for maintaining undegraded postural equilibrium have not been established. Also not known is the level at which the proprioceptive cues become useless in orientation although, as mentioned, tilt tests in water indicate judgment is impaired, with the degree of impairment reduced by training.

In summary, it appears that the otolith and proprioceptive sensors will be directly affected by a reduction in gravity while vision and the semicircular canals will be relatively unaffected. Complete loss of two of the general sensors probably removes the possibility for man to maintain his equilibrium, especially if vision is involved. However, there still remains some question as to the effects on equilibrium of reducing the stimulus to two of the sense organs to only 1/6 of the normal as would be the case in lunar conditions. Some insight into this problem may be gained from the following discussion of the self-locomotion experiments of reference 8, performed on the lunar-gravity simulator at Langley Research Center.

NOMENCLATURE

The following, together with figure 1, define the symbols used herein:

δ_b back angle, angular deflection of the reference line joining the hip and shoulder joints relative to the vertical, degree

δ_h hip angle, angular deflection of upper leg (thigh) relative to the back reference line, degree

δ_k knee angle, angular deflection of the lower leg relative to the upper leg, degree

δ_a ankle angle, angular deflection of the foot relative to the down leg (calf), degree

ω_h rate of change of hip angle, degrees per second

ω_k rate of change of knee angle, degrees per second

g gravitational unit, relative to acceleration produced by earth's gravitational field

T time, second

V velocity, feet per second

Subscript:

max maximum value

DESCRIPTION OF REDUCED-GRAVITY SIMULATOR

A sketch of the simulator is shown in figure 2. The simulator supports a subject on his side, inclined about 9.5° from the horizontal, for lunar simulation, by means of a system of cables attached to the various body members and to an overhead trolley system. The trolley unit moves along an overhead track which is parallel to the walkway on which the subject is free to walk,

run, and perform other self-locomotive tasks in essentially a normal manner though constrained to move in one plane. This constraint does not appear to be too serious if one considers the fact that the body members normally translate and rotate, fore and aft and up and down, essentially in parallel planes as a person walks, runs, and jumps in a normal manner. Figure 3 shows a subject in the simulator cable harness. As mentioned, the subject is inclined 9.5° from the horizontal and the component of his weight normal to the walkway and supported by his feet is 1/6 that of his normal weight as would be the case in lunar gravity. The 1/6g component is therefore considered to be the one which is important for balance and locomotion in the plane normal to the walkway.

It is recognized, of course, that there remains a 1 g vector acting on the body. It should be pointed out, however, that this vector is essentially constant during normal simulator usage and people readily adapt to their new orientation by recognizing the tilted walking board as the ground plane and relating their body motions to it rather than the customary ground reference. One of the limitations of the simulator is that the subjects' motion is restricted to one plane and the simulator is not adaptable to studies requiring out of plane motions. Despite this limitation, the simulator is useful for studying man's equilibrium and motion capabilities in the sagittal plane under reduced gravity conditions. For the investigation discussed herein the simulator was used with the subject's vision unrestricted and with the walkway displaced to provide the lunar level of stimulation to the otoliths and the kinesthetic sensors in the plane of activity.

MEASUREMENTS

All tests were recorded by means of the motion-picture cameras operating at 24 and at times 48 frames per second. An observer using a stop-watch obtained the time required to travel the 100-foot distance in the middle portion of the walkway. This time was used to establish the average velocity for each test.

Positions and rates of movement for the various body members relative to each other and to the ground were obtained from measurements of the projected images of the motion-picture film. The accuracy of the angular measurements is considered to be about $\pm 2^{\circ}$.

RESULTS AND DISCUSSION

A film supplement illustrating some of the results of this investigation is available for loan purposes. A request form can be found at the end of this paper.

Some of the subjective results of the present investigation indicated that the subjects tested, initially, had some difficulty in sensing the vertical to the walkway and stood rocking to and fro perhaps trying to increase the vestibular response. The subjects also ended up standing on tip toe in an apparent attempt to increase the stimulus to the tactile and pressure sensors and thereby improving their balance. It is expected that this will also be the case on the lunar surface. Several subjects indicated a sensation of being inclined after leaving the device indicating adaptation to the constant lateral tilt required when using the simulator. Adaptation to continued tilt was expected on the basis of the experiments of reference 9 conducted with animals.

In these experiments measurements of neural impulses indicated a vigorous initial response to tilt which diminished in about 20 or 30 seconds with the steady-state response to tilt relatively weak. In the present experiments it was found that with little practice the subjects were able not only to maintain their static equilibrium but could walk, run, and perform other self-locomotive tasks which indicates that man will find it relatively easy to adapt to the lunar conditions.

Some data were obtained for three subjects comparing the difference in posture and limb motion during locomotion for earth and lunar gravity conditions and the results are presented in figures 4 through 12. The discussion herein will be limited to those aspects which it is felt are important for equilibrium and which indicate the extent of control and coordination of the motion of various parts of the body. (For a discussion of the data relative to locomotion characteristics, see ref. 8.)

Figure 4 reconstructed from the film records presents qualitatively the difference in posture and position of the body members for the subjects walking, loping, and sprinting in the earth and simulated lunar gravity conditions. The figure is in the form of line diagrams (stickmen) presented at about 1/6-second intervals giving time histories of body member positions for at least one step as denoted by the solid horizontal bars at the ground level. The comparison made for sprinting is for the maximum sprinting speed which turned out to be 19.8 feet per second for earth gravity and 13.1 feet per second for simulated lunar gravity. The lower value of maximum sprinting speed in lunar gravity is attributed to the loss of traction in 1/6g. From the figure it is readily seen that there are relatively large differences in locomotion characteristics for the two gravity conditions. This is also

apparent in figures 5 through 7 in which data corresponding to that of figure 4 are presented in quantitative form. The symbols in these figures indicate the beginning and end of a step. From figures 5 through 7 it can be seen that there are large differences in amplitudes and rates of motion of the various body members for the different gravity conditions as well as large differences in the body lean or back angle. There is also a large variation of back angle with locomotive rate. This is more easily seen in figure 8 which is a plot of back angle versus locomotive rate. Figure 8 shows that the back angles increased at a much higher rate for simulated lunar gravity than for earth gravity and resulted in angles as high as 60°. These angles are 3 or 4 times greater than the maximum obtained in the 1 g environment. Figure 9 shows how the body lean or back angle affects the component of gravity along and perpendicular to the subject's body.

The components are simply sine and cosine functions of the body lean angle as indicated in the figure. The data in the figure illustrate that even though the component along the body in simulated lunar gravity is decreased by 50 percent when leaning from 0° to 60° it is still considerably greater than the threshold value indicated by the solid horizontal line. The component normal to the body increases with body lean but the maximum obtained for simulated lunar gravity at 60° is much less than that obtained at the maximum body lean angle of 20° used in earth gravity. Figure 10 shows the variation with velocity of body lean angles for one of the subjects carrying various loads in simulated lunar gravity. The data show that as the total weight, that is the weight of the subject plus weight of his load, approaches that of the man with no load in earth gravity, the rate of increase of lean generally decreases and is more nearly like that for man with no backpack in earth

gravity. This would appear to indicate that the large body lean used by the subject in simulated lunar gravity is related more to the mechanics of locomotion rather than an attempt to modify the stimulus to the vestibular organs. Since the subject carried the weights in a frame mounted on his back, an initial upper body lean or back angle was required to keep the resultant center of gravity over his hip joint. This initial lean accounts for the large upper body lean angles used, even at low locomotion velocities, by the weight-carrying subject. It should be pointed out that despite these large body lean angles the subject had no trouble in maintaining his balance while walking or running on the simulator. An analysis of the restraints of the simulator is given in the appendix of reference 8 and indicates that only about 5° of the maximum lean angle is a result of the restraints considered.

The data of figures 11 and 12 summarize other differences in the relative motions of the various body members. First of all, as illustrated in figure 11(a) the hip flexion angles are larger for the lunar condition than for earth gravity indicating that the legs were carried farther forward in the lunar gait than in earth gaits. This is attributed to the fact that with the large body inclinations noted the legs had to be carried farther forward to maintain balance. This in turn resulted in decreased knee flexion, figure 11(b), and gave the subject an appearance of walking stiff-legged for the lunar simulation. It appears likely that the normal knee action is not required for lunar activities with the weight on the legs relatively low.

As shown in figure 12, there was also a difference in rates of limb motion for earth and simulated lunar walking. The maximum angular rates for hip and knee motions for lunar walking were about one-half that for earth walking.

The results of these experiments generally indicate that the subjects are able to adapt their limb motions to the decreased gravity conditions and are able to maintain equilibrium even while running at about 13 feet per second. Indeed, as the short film supplement will show, man can also jump and perform acrobatics using the simulator, indicating the ease with which man accommodates to the unusual environment. Some experiments performed with the subjects wearing a suit pressurized to 3.7 psi indicated that wearing a pressurized suit would not affect the results enough to alter the general conclusions reached herein pertaining to man's equilibrium. Of course, it is assumed that the suit would not severely restrict the subject's vision.

CONCLUDING REMARKS

On the basis of the observations and tests examining man's ability to perform under the reduced gravity conditions on the lunar surface it appears reasonable to assume that, with some training, man will be able to maintain his equilibrium and orientation while moving on the lunar surface. It is suggested, however, that experiments in reduced-gravity simulators as well as in 1/6g parabolic flights be continued to obtain additional pertinent information.

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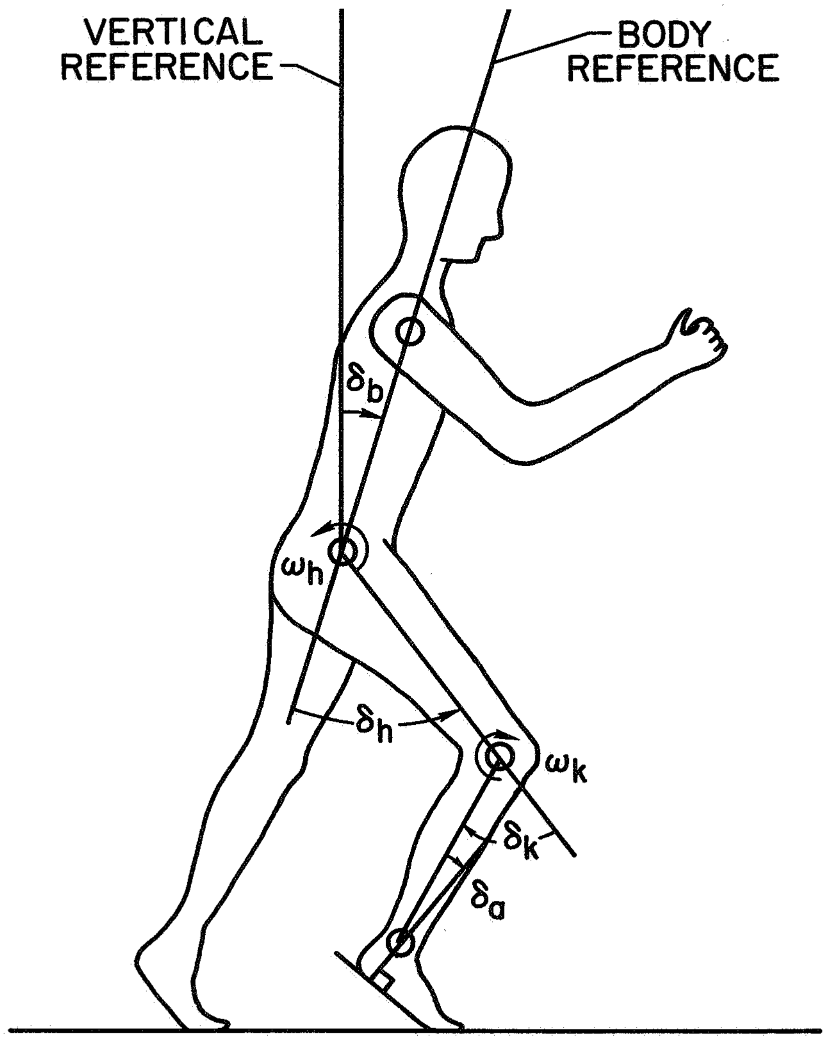


Figure 1.- Definition of body angles. All angles are positive as shown.

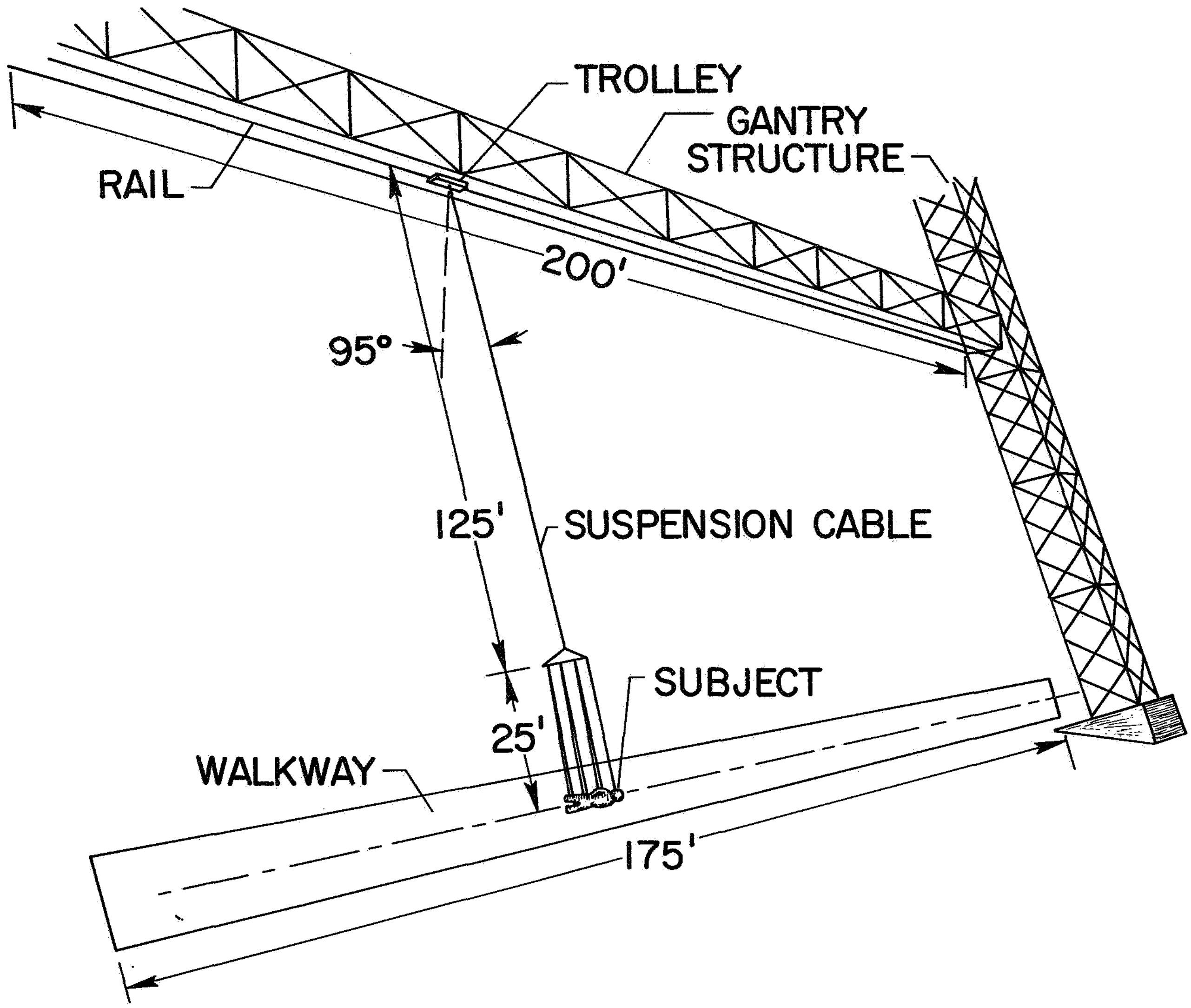


Figure 2.- Illustration of the reduced gravity simulator.

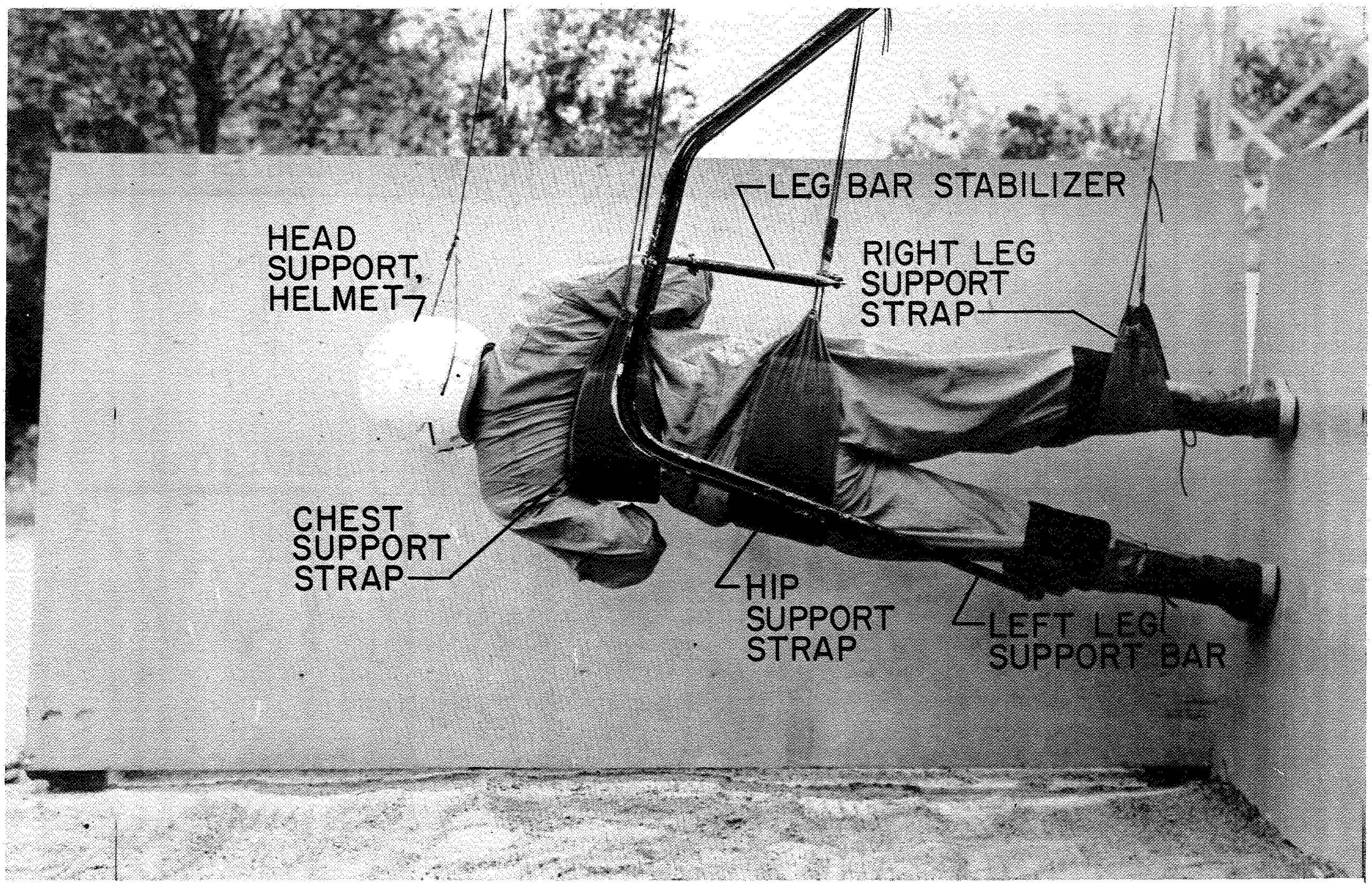
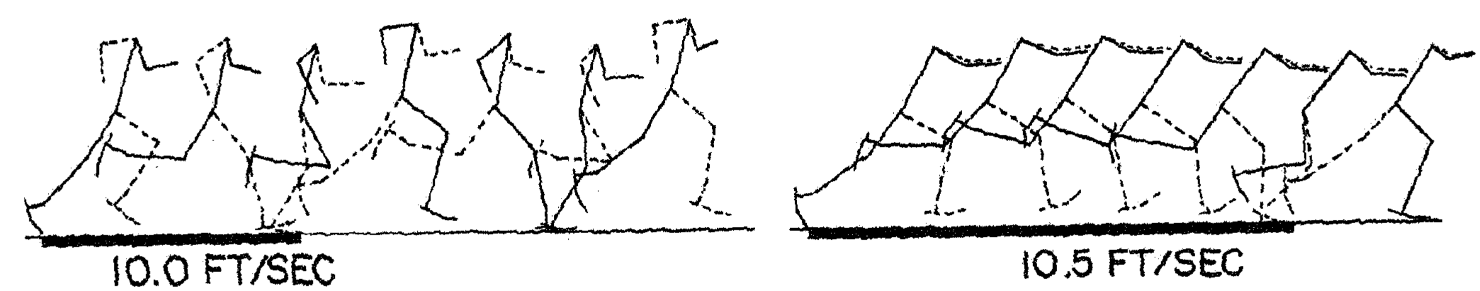
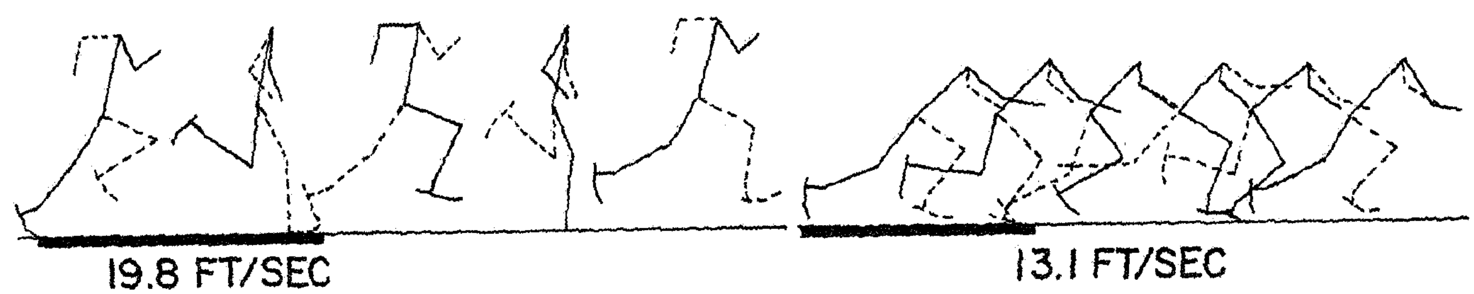


Figure 3.- Body harness details.

(a) Walk.



(b) Lope.



(c) Sprint.

Figure 4.- Stickman representation of a typical walk, lope, and sprint in earth and lunar gravity. Length of bar at ground line denotes distance of one step. Dashed line denotes position of the left arm and leg. The time interval between each figure is 0.16 second.

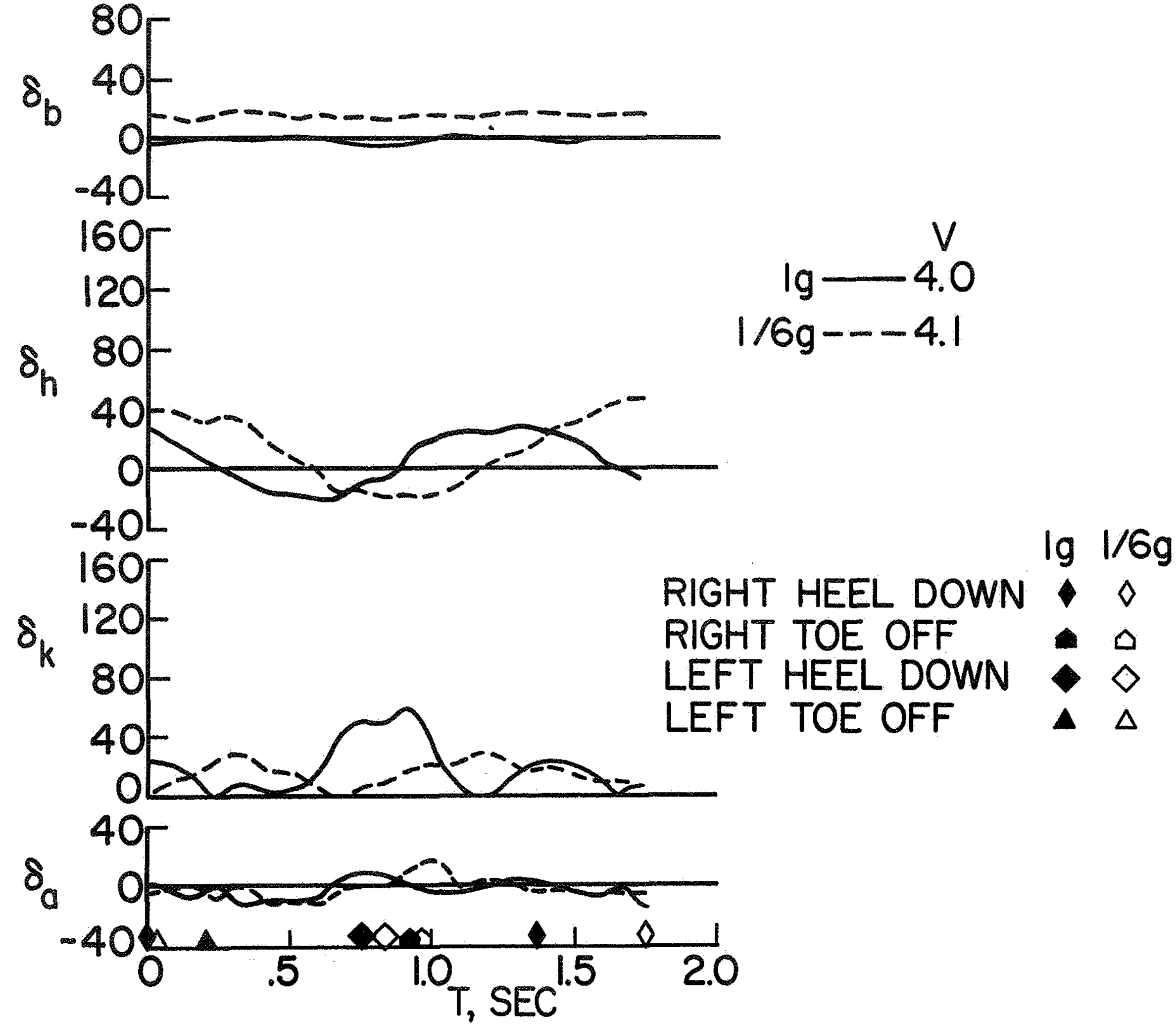


Figure 5.- Time history of the relative motion of various body members while walking in earth and lunar gravity.

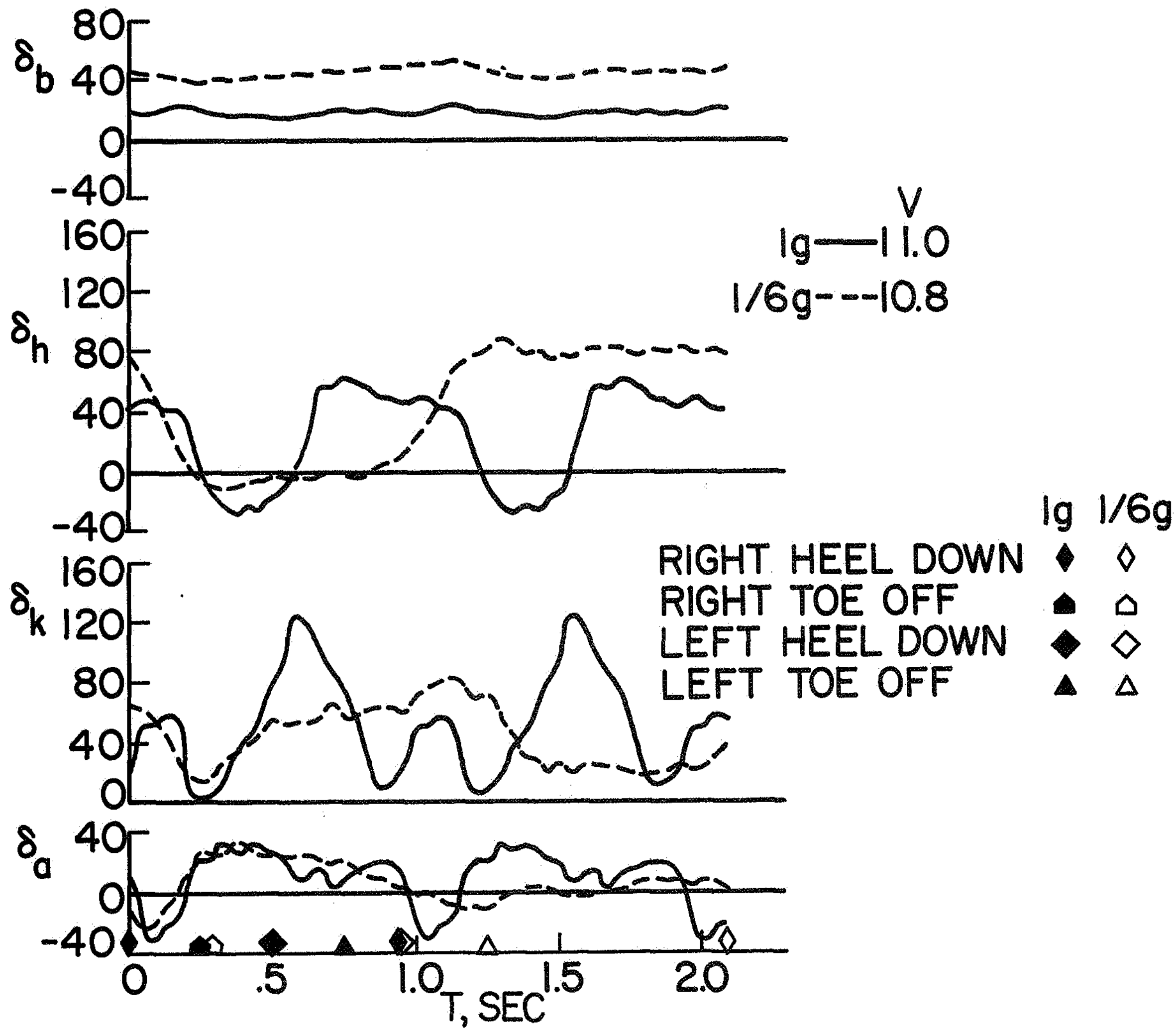


Figure 6.- Time history of the relative motion of various body members while loping in earth and lunar gravity.

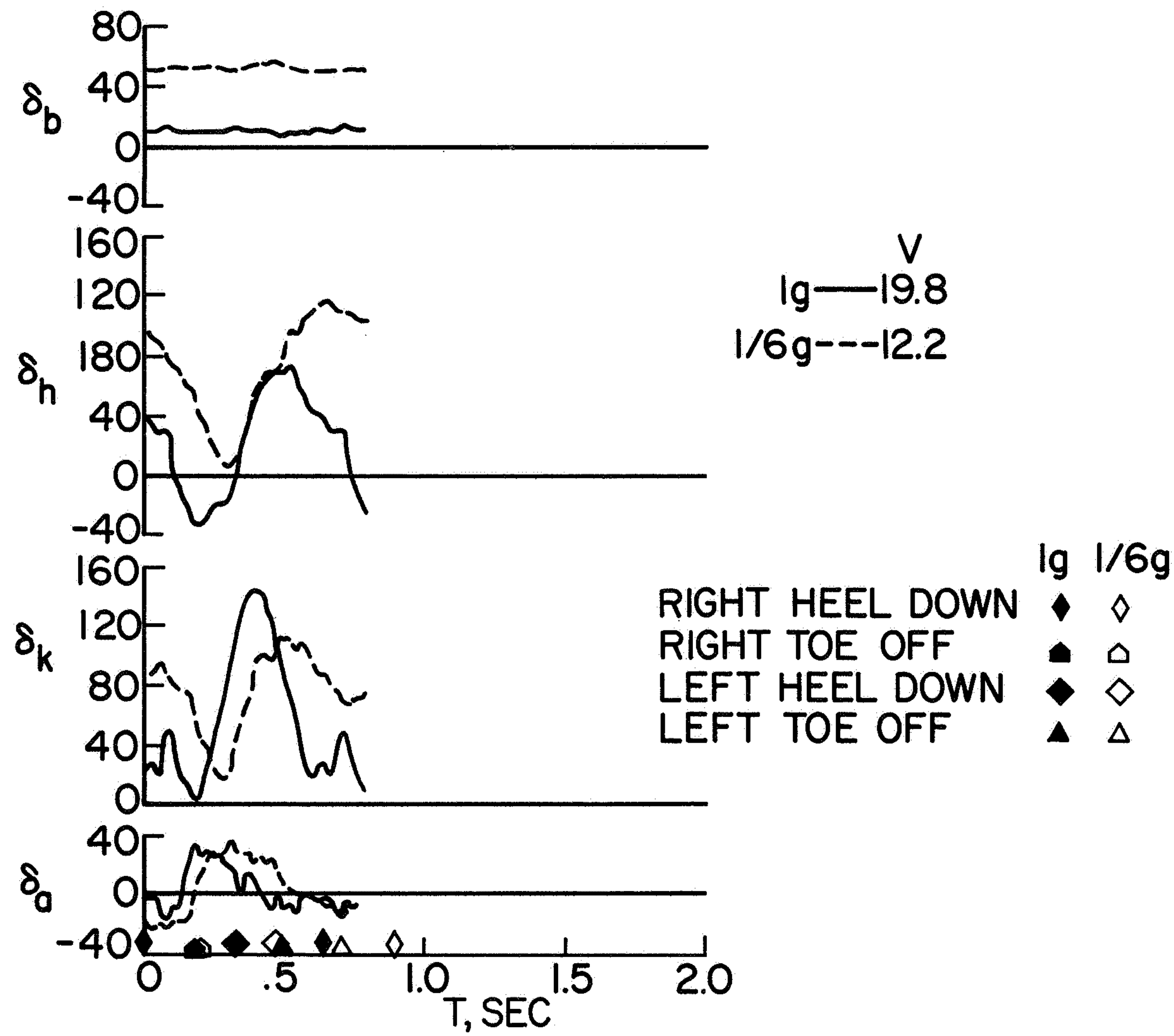


Figure 7.- Time history of the relative motion of various body members while running at maximum velocity in earth and lunar gravity.

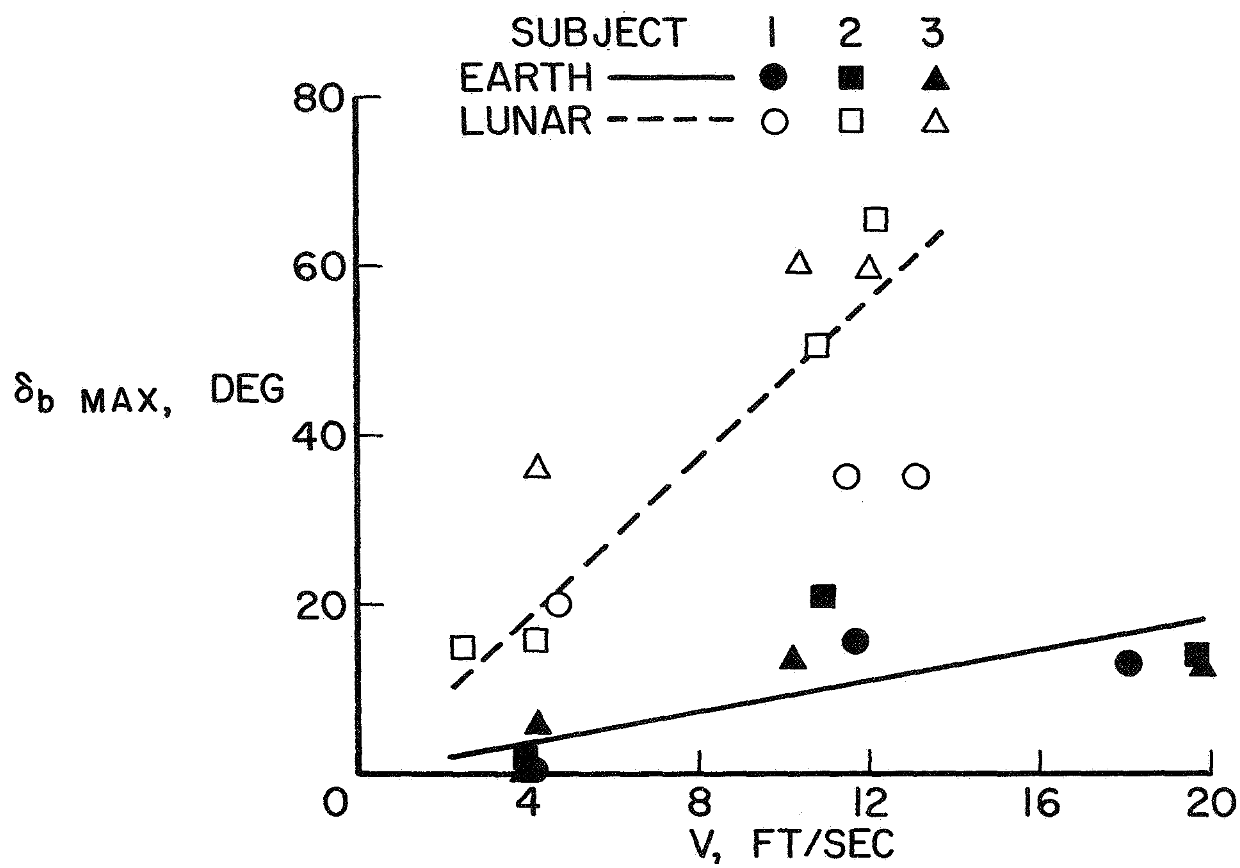


Figure 8.- Maximum body lean or back angle versus locomotion rate at 1g and $\frac{1}{6}$ g.

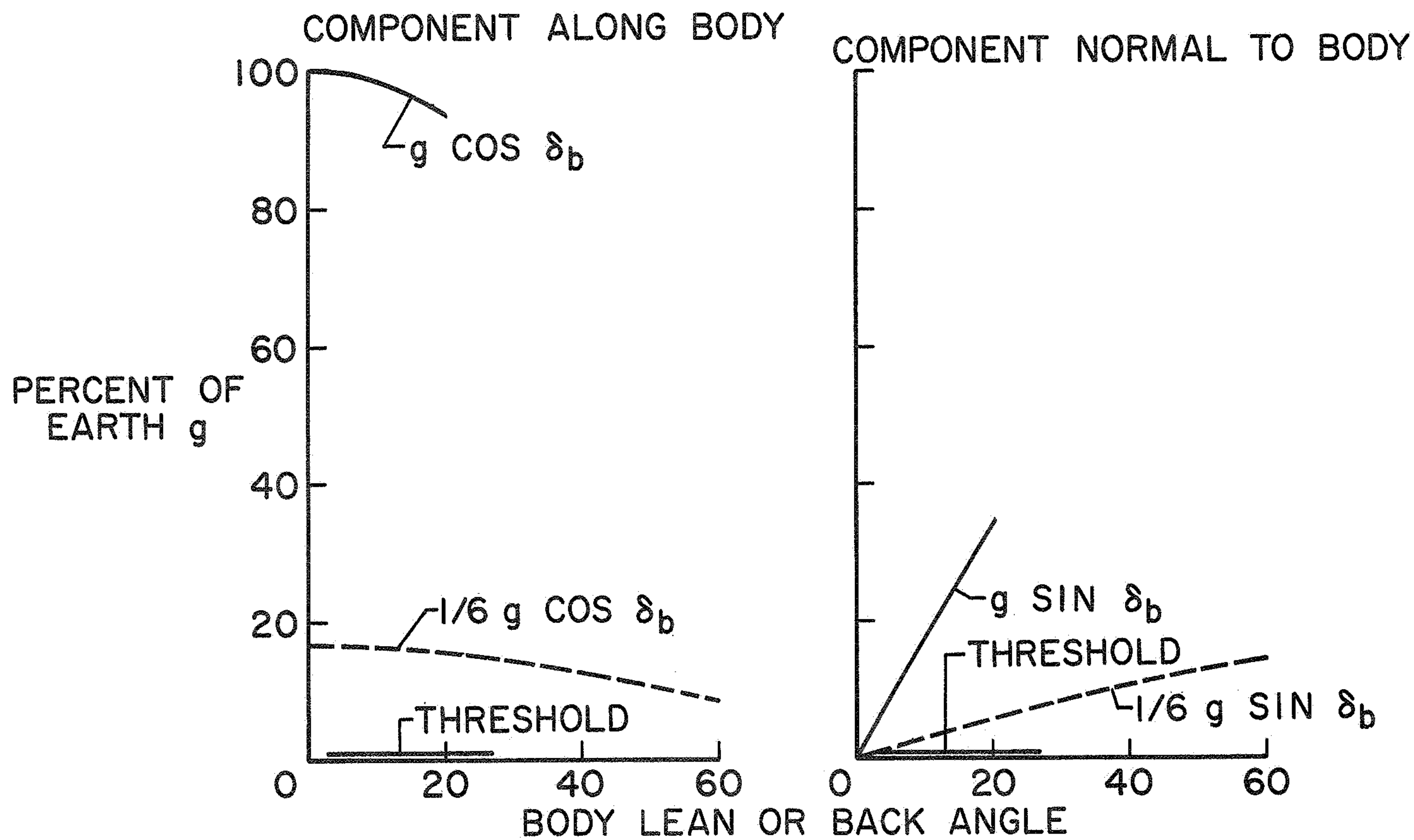


Figure 9.- Gravity components versus body lean or back angle for 1 g and $\frac{1}{6}$ g.

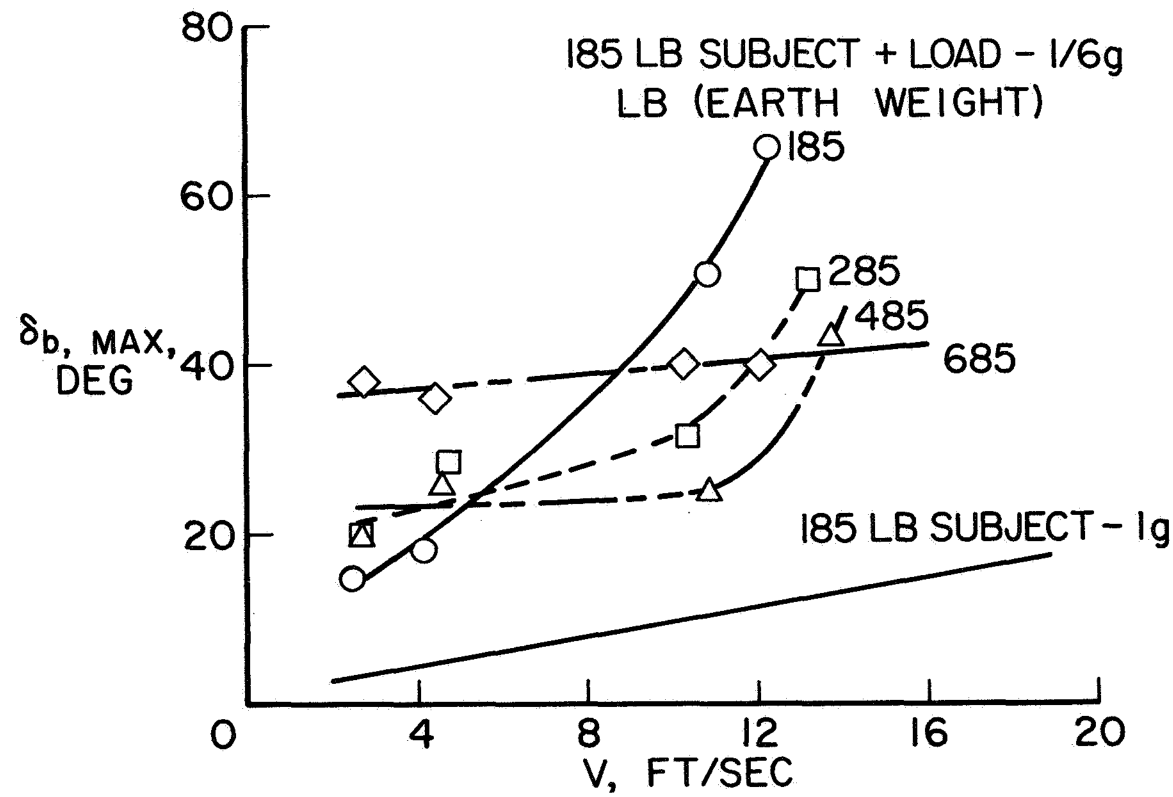
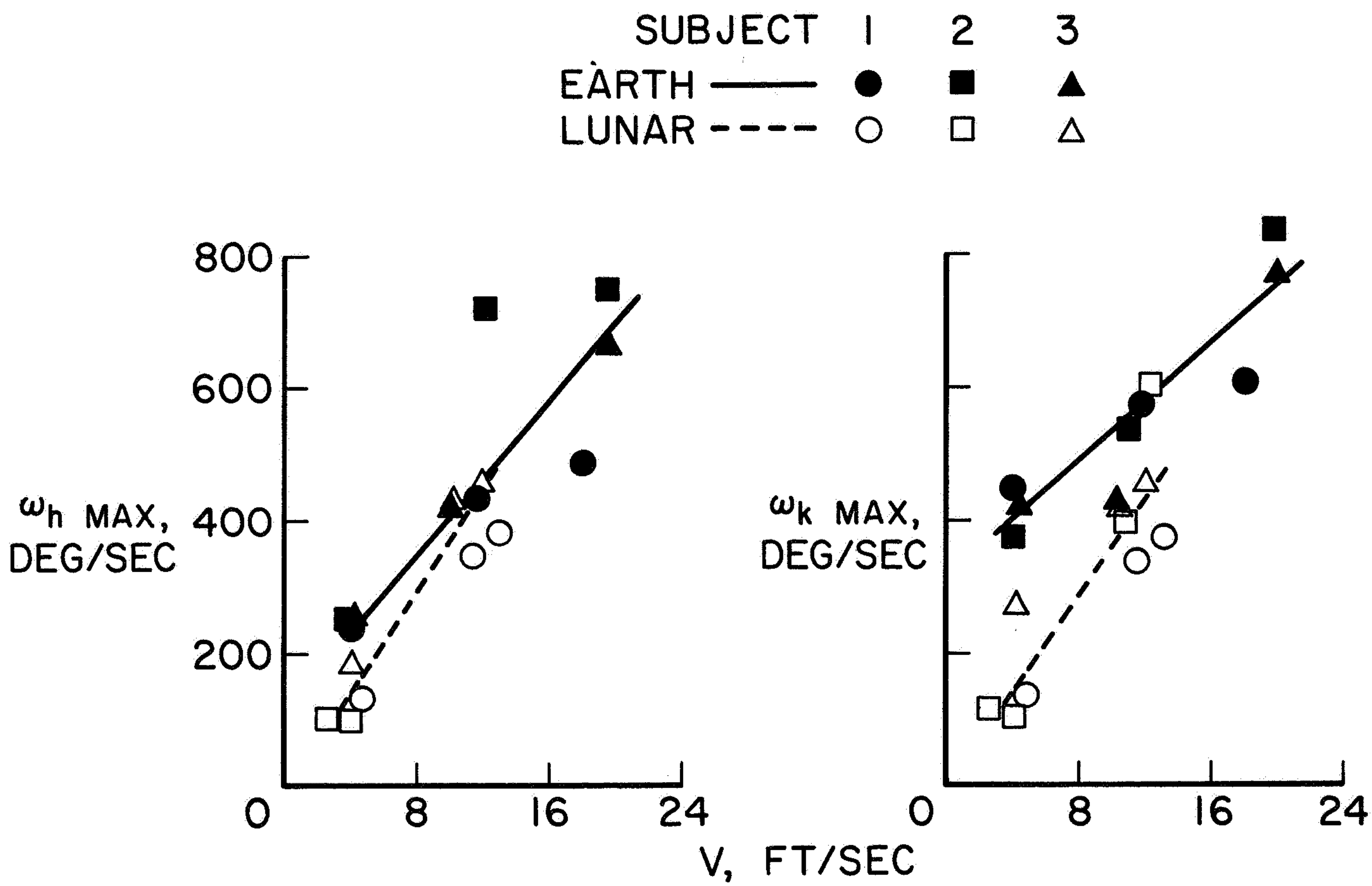


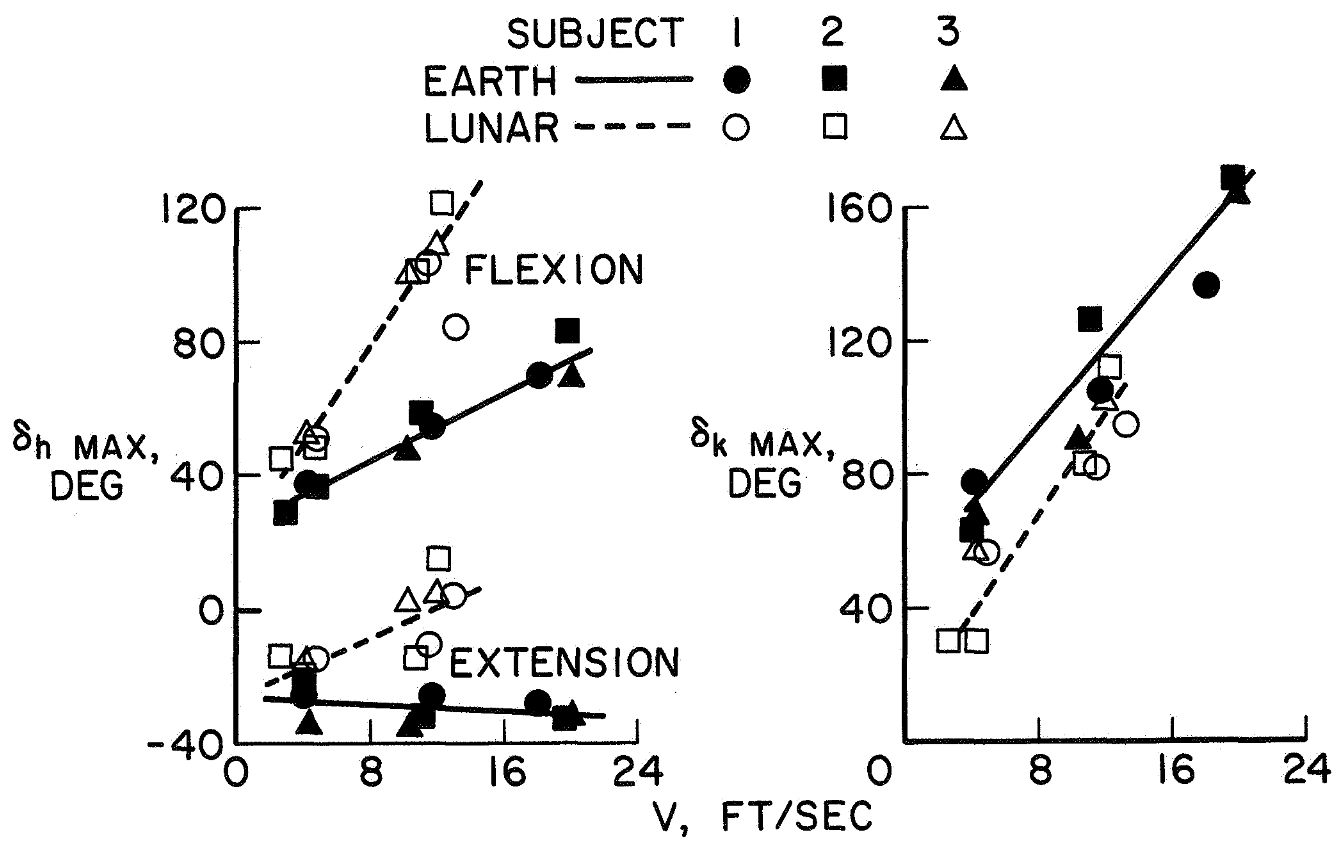
Figure 10.- Maximum body lean or back angle versus locomotion rate with subject carrying various loads



(a) Upper leg displacement.

(b) Lower leg displacement.

Figure 11.- Maximum upper and lower leg displacements, as indicated by $\delta_{h_{max}}$ and $\delta_{k_{max}}$, versus locomotion rate in 1 g and $\frac{1}{6}$ g.



(a) Upper leg rate.

(b) Lower leg rate.

Figure 12.- Maximum upper and lower leg rates, as indicated by $\omega_{h_{max}}$ and $\omega_{k_{max}}$, versus locomotion rate in 1 g and $\frac{1}{6}$ g.

NASA-Langley, 1966